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MEMORY IMPAIRMENT AFTER COMMISSUROTOMY IN MAN

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PATIENTS with cerebral commissurotomy appear to casual observation to be remarkably free of behavioural impairment in ordinary activities. Conversational facility, verbal reasoning and intelligence, established motor co-ordination, long-term memory, personality, sense of humour, mannerisms, temperament, and social interactions all show surprisingly little disruption after one to two years recovery from the single stage operation performed by P. J. Vogel and J. E. Bogen (Bogen, Fisher and Vogel, 1965). The numerous deconnexion symptoms that have been documented in these patients (Sperry, 1968, 1973; Sperry, Gazzaniga and Bogen, 1969; Gordon and Sperry, 1969) are mostly demonstrable only under lateralized testing conditions where at least one phase of the total performance can be restricted to a single hemisphere.

An exception to the foregoing has been noted in that all the patients have exhibited marked and persistent difficulty with short-term memory as observed particularly by relatives and other close associates. The patients forget telephone messages and appointments, for example, and cannot recall where they have placed personal items. They repeat the same anecdotes many times to the same audience, have exceptional difficulty in relocating a parked car, etc. The severity of the deficit varies in different cases but is definitely evident even in the youngest patient with least extra commissural brain damage. No comparable loss of memory has been noted for childhood events or even for events occurring a year or so before the operation.

It has been shown in numerous specialized tests which involve some memory performance that each of the disconnected hemispheres is quite capable of storing and retrieving new information (Gazzaniga and Sperry, 1967; Sperry, 1968; Milner and Taylor, 1972; Kumar and Sperry, 1971; Zaidel and Sperry, 1973*a*). Only exceptionally in lateralized tests however has the level of performance approached that to be expected under comparable conditions with commissures intact. This is true even where the test tasks have been designed to be as purely left or right hemisphere as possible (Levy, 1969*a*; Nebes, 1971; Kumar, 1971).

Definite improvement in memory has been evident during the first year in all patients and has seemed to progress gradually at a declining pace into the third post-operative year or longer. First it seemed that the memory difficulty might almost disappear after five years or so, but this has not been so and the present study was undertaken to assess further the nature and relative severity of long-term effects of commissurotomy on memory. From the findings obtained with six standardized tests administered to a group of 10 commissurotomy patients, it is inferred that the human forebrain commissures play an important selective role in mnestic function.

SUBJECTS

Eight of the patients to whom the tests were administered had presumed complete sections of the corpus callosum, hippocampal and anterior commissures. The massa intermedia was also sectioned in N. G. and N. W. (Bogen, Fisher and Vogel, 1965). Two additional patients were tested in whom only the anterior two-thirds of the corpus callosum was sectioned along with the anterior commissure sparing the splenium. The general deconnexion effects in these cases with the partial commissurotomy have been described and compared with the results of complete section (Gordon, Bogen and Sperry, 1971). The surgical approach to the anterior commissure involved the columns of the fornix. Complete section of the right column was recorded in N. G. and of the left column in D. M. At least partial interruption of columnar fibres in the other cases cannot be ruled out.

The age of the patients at the time of the present study and the number of years intervening since operation are shown in Table I. Extracallosal damage not associated with the surgery must be inferred to be present in all cases, varying widely in nature and extent, with the involvement minimal in L. B. and N. G. When this study was undertaken all patients were under some mild to moderate anticonvulsive medication though the dosages were substantially reduced from those before operation. For further information on the histories see Bogen (1969).

TABLE I.—PATIENTS' AGE DURING ADMINISTRATION OF PRESENT TESTS AND NUMBER OF YEARS AFTER OPERATION

Patients		*Age tested*	*Years after operation when tested*
Complete commissurotomy	L. B.	20	7
	R. Y.	48	6
	N. W.	41	5½
	N. G.	38	8½
	C. C.	20	7
	R. M.	33	6
	M. K.	34	4½
	A. A.	21	7½
Partial commissurotomy	N. F.	30	3½
	D. M.	27	4

METHOD

Each of the 10 right-handed subjects was given the same battery of 6 standardized tests for memory as listed below. Standardized procedures were followed throughout with no attempt to restrict for hemispheric lateralization. The tests were all administered and scored according to the standard manual instructions.

Wechsler Memory Scale (WMS).—All 7 of the subtests were given. These cover a wide range of memory functions including general information, logical memory, paired associate learning, and counting forward and backward. Except for one, Figure Reproduction, all subtests required verbal answers. The total raw scores are normally adjusted for age and the corrected score assigned a Memory Quotient (MQ) value based on the standardization sample. An MQ of 100 indicates average ability (Wechsler, 1945).

Benton's Revised Visual Retention Test (VRT).—Forms C and D were presented using Administration A. Each of 20 line drawings of geometric forms was exposed on a card for ten seconds following which the subject tried to reproduce the pattern by drawing from memory. Most of the 20 cards contained up to three patterns of two different sizes. The score considered here is in terms of number correct reproductions. A score of 16–20 correct indicates an "average to very superior level of competence"; 10–14 is "defective to low or dull" (Benton, 1963).

Memory for Designs (MFD).—This is an easier task than the preceding VRT and thus permits additional assessment of memory ability. The test consists of 15 cards with geometrical drawings with only one figure per card. Each drawing was exposed for five seconds and after its removal the subject attempted to reproduce it on paper. The score is the total number of errors. Raw scores of 12 or more indicate brain damage; normal is 0–4, and 5–10 is borderline (Graham and Kendall, 1960).

Knox Cube Test (KCT). *A subtest of the Arthur Point Scale of Performance, Revised Form II.*—Four one-inch cubes mounted in a line 2 in. apart on a wooden base were tapped selectively by the examiner after which the subject tried to duplicate the exact tapping sequence. Lengthened complexity of the sequences increased until the subject failed on three successive trials. The score is based on the average of two administrations of the test (Arthur, 1947). The test manual provides only children's norms, but a published study by Sterne (1966) provides adult norms which also were used for comparison with the present results.

Visual Sequential Memory (VSM). *A subtest of the Illinois Test of Psycholinguistic Abilities* (ITPA).—This tests the reproduction from memory of progressively long sequences of meaningless figures. The subject was shown a printed sequence of figures for five seconds and after its removal, attempted to arrange a corresponding series of chips in the exact same order, with a second trial allowed if the first failed. The score is based on the number of correctly reproduced sequences. To date only children's norms are available up to ten years and three months with which the present scores are compared (Kirk, McCarthy and Kirk, 1968).

Memory Span for Objects (MSO) *of the Mental Examiner's Handbook.*—Line drawings of 20 objects familiar to men and another group of 20 picture objects more familiar to women were shown to the subject, who then named aloud each picture as pointed to by the examiner. Each group of 20 pictures was tested separately. Following the 20th response the book was closed and the subject was asked to rename as many of the 20 items as he could remember. The score is the number of items recalled. An average adult is expected to remember at least 11 objects of a 20 picture group (Wells and Ruesch, 1945).

Additional WAIS scores reported in this study were obtained from Levy (1969*b*) and some of the VSM scores were obtained from E. Zaidel (1973).

RESULTS

Individual and average scores for all six tests along with the WAIS Full Scale IQ are presented in Table II. Subnormal mean scores in all patients on all tests, verbal and non-verbal, indicate memory impairment varying from moderate to marked.

TABLE II.—INDIVIDUAL AND AVERAGE SCORES ON THE SIX STANDARDIZED MEMORY TESTS WITH WAIS IQ FOR COMPARISON

	Complete commissurotomy									*Partial commisurotomy*		
	N.G.	*L.B.*	*A.A.*	*R.Y.*	*N.W.*	*C.C.*	*R.M.*	*M.K.*	$\bar{X}$	*N.F.*	*D.M.*	$\bar{X}$
WAIS IQ												
Full scale	77	106	78	90	93	72	80	69	83	83	76	79·5
WMS												
MQ	64	80	63	77	70	58	57	50	65	63	58	60
VRT												
Number correct	3	18	5	6	4	4	4	4	6·2	7	8	7·5
MFD												
Number of errors	12	0	6	7	13	10	8	8	8	3	0	1·5
Difference score	8·5	−3·5	2·5	3·5	9·5	6·5	4·5	4·5	4·5	−·5	−3·4	
KCT												
Raw	7	15	8	9	8·5	10	5	5	8·4	11	8	9·5
VSM												
Raw	18	17	19	15	14	20	18	14	16·8	19	23	21
Scaled	18	27	30	24	22	31	28	22	26·5	36	30	33
MSO												
Women	6	13	10	4	10	5	3	8	7·6	12	3	7·5
Men	8	9	11	4	9	9	6	6	8	6	5	5·5

Comparisons between Intelligence and Memory Quotients show memory to be substantially more affected than general intellectual capabilities.

The overall performance of L. B. came closest to normal, but even so the 26 point discrepancy between his IQ and MQ was greatest in the entire group. Those with partial commissurotomy obtained on the average somewhat higher scores on 4 of the tests. On only 2 of these, however, MFD ($t=2·15$, $P<·05$) and VSM ($t=4·72$, $P<·01$), were the differences between the two groups significant. Moreover, the IQ-MQ difference was essentially the same in both groups (18 points for complete commissurotomy and 19·5 for partial). Further description and breakdown of the results is given below with reference to specific tests.

Wechsler Memory Scale.—This test with the seven different subtests was the most comprehensive of the six tests administered. Fig. 1 compares the mean performance of patients to that of normal subjects of equivalent age (Wechsler, 1945). All average scores fell below the norm, including that of the youngest patient, L. B., in whom there was least extra-callosal damage and highest degree of functional compensation (*see* Discussion). The complete commissurotomy patients had greatest difficulty with Visual Reproduction. This task is presumed to depend most

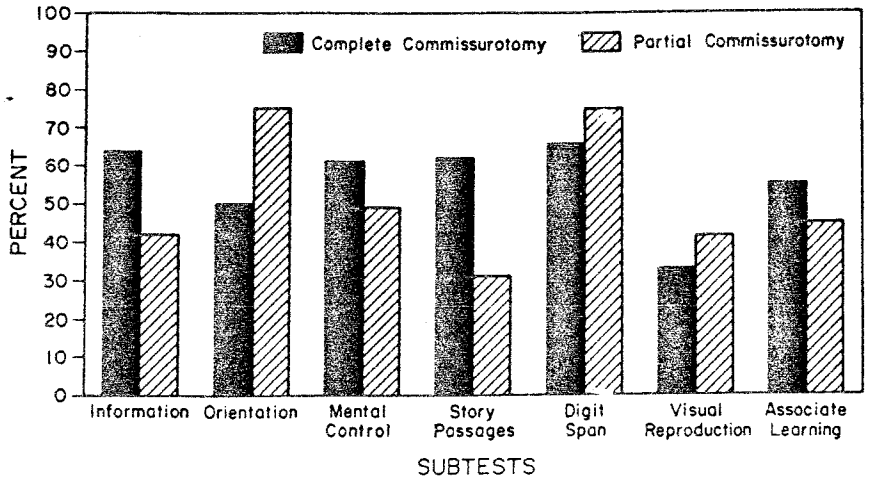

FIG. 1.—Comparison of mean performance of patients with mean of normal adults on WMS.

strongly on visual spatial ability. The partial commissurotomy patients did most poorly on Story Passages, the most semantically complex of the subtests. The two partial cases exhibited unusual difficulty in recalling ideas or specific facts. Their performance did not improve after reading the stories by themselves (instead of hearing them read by the examiner) when the two prose sections were presented again a few weeks later.

The possible role of visual imagery in semantic memory is suggested in the consistent excessive difficulty with novel as compared to common word associations ($t=8{\cdot}11$, $P<{\cdot}001$, in completes; $t=7{\cdot}23$, $P<{\cdot}001$ in partials). Table III presents actual breakdown of scores obtained on Associate Learning and Story Passages subtests. These differences are on the average 41 times greater than in normal subjects (Wechsler, 1945).

TABLE III.—MEAN SCORES ON TWO WMS SUBTESTS

	Story passages		*Word association*	
	"A"	"B"	"Easy"	"Hard"
Complete commissurotomy	6·62	4·37	7·00	1·00
Partial commissurotomy	4·0	1·5	6·25	1·00

Visual Retention Test and Memory-for-Designs.—These two visuo-constructive non-verbal retention tests have similarities but differ in difficulty and hence together permit a broad span assessment of memory. Mean performance on both was below normal. The mean correct score on the VRT was 14 per cent lower than that for controls of similar age and IQ (Benton, 1955), with L. B. alone scoring in the normal range. On the simpler MFD the patients' mean correct scores were 33 per cent higher than on VRT with three patients, L. B., N. F. and D. M., performing within the normal range. If L. B.'s exceptionally high scores were excluded on both tests then mean correct performance would drop by 10 per cent on the VRT and 5 per cent on MFD.

The fact that errors were on the average 1·85 greater for the right half of each VRT drawing seems most simply accounted for by the fact that reproduction of the designs always begins with the left-most figure. Sixty-eight per cent of all errors on VRT were distortions and only 2 per cent were size errors. In view of qualitative differences in design reproduction associated with left and right unilateral lesions (Warrington *et al.*, 1966; Gainotti and Tiacci, 1970) the results can be ascribed to left hemisphere dominance after commissurotomy.

Knox Cubes and Visual Sequential Memory.—These two tests involving non-verbal sequences of increasing length permitted a comparison of temporal and spatial serial memory. Performance was subnormal on both tests, the mean score on KCT being equivalent to age 8 of normal children and that on VSM equivalent to age 6. The mean raw score obtained by all patients on VSM was 14 per cent lower than the mean raw score obtained by normal adults with less than 98 IQ and mean age of 48 (Sterne, 1966).

The three serial tests, KCT, VSM and verbal Digit Span subtest of the WMS, measured different aspects of serial memory. When length of recalled sequences was examined in each, the upper limits that could be remembered in sequence by most subjects was found to be 4 or 5 items. No statistically significant differences were found among the three tests.

Memory Span for Objects.—Immediate free verbal recall of highly familiar clustered pictorial material gave a mean raw score 20 per cent below that of normal adults. Individual differences were greater on this than on other tests with subjects remembering best items most often used. Since the objects were highly familiar a high score could be attributed to pure guessing.

Discussion

The results obtained on these standardized memory tests involving visual reproduction, temporal sequential relations, verbal and logical retention, free picture recall, and related memory factors, revealed consistent marked impairment in short-term memory. In all ten commissurotomy patients the mean scores were below the standard norms and lower than scores of control subjects matched for IQ, and also those published for patients with epilepsy (Quadfasel and Pruyser, 1955; Deutsch, 1953; Milner, 1958; Mirsky *et al.*, 1960). This was true for verbal as well as for non-verbal tasks and regardless of the sensory modalities involved. The findings thus conform with and generally substantiate the impression of near relatives that the patients' short-term memory became impaired after the operation and never recovered to a level even similar to that existing before operation.

Extracommissural brain damage may be presumed to be a possible potentiating factor in the majority of the subjects, but this can hardly be regarded as the predominant cause since the same difficulties with memory were not evident before commissurotomy. Also, the two patients (N. G. and L. B.) in whom such extracallosal damage appears to be minor suffered the same order of memory dysfunction.

The epilepsy itself may also be presumed to be a contributing factor, but impairments of the observed size and perseverance cannot be attributed primarily to the epilepsy. Published reports on the performance of various groups

of epileptic patients on the Wechsler Memory Scale show far smaller discrepancies between intelligence and memory quotients; for example Quadfasel and Pruyser (1955) found a memory deficit in patients with generalized convulsions less by four and a half times that found in the present patients. Milner's (1958) subjects with temporal lobe epilepsy were half as deficient as those with commissurotomy, and in the patients with diffuse foci tested by Mirsky *et al.* (1960) the IQ-MQ difference on the average was three times smaller than found here. Specific comparisons with unoperated epileptics (Deutsch, 1953; Quadfasel and Pruyser, 1955) on test items such as story passages and figure reproduction of the WMS show performance impairments in the present commissurotomy group to be twice as large. As far as can be judged from the observations of the family, constant memory deficits became pronounced only after surgery, even though major seizures were frequent before operation and medication was heavy, whereas during the period of testing seizures were reportedly absent and medication reduced. The combination of epilepsy acting in conjunction with the surgical and other cerebral lesions remains a possible cause that cannot be strictly ruled out. However, the memory impairment seemed to be primarily correlated across the group and also within each subject with section of the commissures, and in the light of considerations outlined below the evidence points to a selective role of the cerebral commissures in mnestic functions.

Commissurotomy makes engrams or parts of engrams stored in the right hemisphere inaccessible to verbal or other recall through the left hemisphere. Similarly engram elements in the left hemisphere would be rendered inaccessible for any task in which the performance is executed by the minor hemisphere. In addition, however, it was found that memory traces for highly verbal, presumably left hemisphere, tasks were also subnormal. This suggests that more is involved than just inaccessibility of contralateral engrams. Not only engram retrieval and readout, but perhaps also the initial encoding of memory may be facilitated through interhemispheric interaction. This is supported by the observation that long-term memory especially for events before commissurotomy seems to be much less impaired than does short-term memory. The same observation further suggests the possibility that long-term memory for events is largely verbalized, perhaps through repeated rehearsal, and stored mainly in the left hemisphere (Sperry, 1973).

It is significant that the two patients with only partial section of the commissures also obtained subnormal scores on the majority of tests. This similarity in memory impairment contrasts with the marked differences between partials and completes in basic deconnexion symptoms (Gordon *et al.*, 1971). On the other hand, the partial cases scored higher on non-verbal presumed right hemisphere tests but lower on some of the verbal left hemisphere tests. The frontal two-thirds of the callosum thus seems to be implicated as being involved in mnestic functions even for highly verbal semantically complex material such as the prose passages on the WMS test.

The relatively higher scores obtained by L. B. seem to correlate in part with his higher IQ but they can also be attributed to improved methods in mechanism for

right-left integration achieved through re-education and functional compensation (Zaidel and Sperry, 1973*b*). His high scores on the MFD and VRT for example may reflect the improved ability of the minor hemisphere in this subject to gain expression through control of the right hand. In spite of this the disparity between L. B.'s IQ and his MQ was the largest in the patient group.

The fact that L. B. obtained memory scores essentially in the normal range on the KCT, MFD, MSO and VRT tests suggests that memory *per se* may not be impaired where ability to perform is well within the capacity of a given hemisphere. In other words, the basic mechanism of engram formation may not be impaired, only the associated processes which involve interhemispheric co-operation; for example, consistent deficits in word-paired associate learning in WMS may be ascribed to lack of visual imagery support from the right hemisphere. Taken collectively the results support the conclusion that the interhemispheric commissures are important to memory especially in the initial grasping and sorting-for-storage of perceived information, and at later stages in the retrieval and read-out of contralateral or bilateral engrams.

Summary

Ten commissurotomy patients (8 with complete and 2 with partial section of the forebrain commissures) obtained subnormal scores on a battery of 6 standardized tests for assessment of memory. Although the observed memory impairment is presumed to have been amplified by extracommissural brain damage in most of the cases, it is concluded that the loss of the cerebral commissures is mainly responsible and that these commissures serve selective mnestic functions. In particular the data suggest that processes mediating the initial encoding of engrams and the retrieval and read-out of contralateral engram elements involve hemispheric co-operation and depend upon the function of the interhemispheric commissures.

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